Computational accelerator science needs towards laser-plasma accelerators for future colliders

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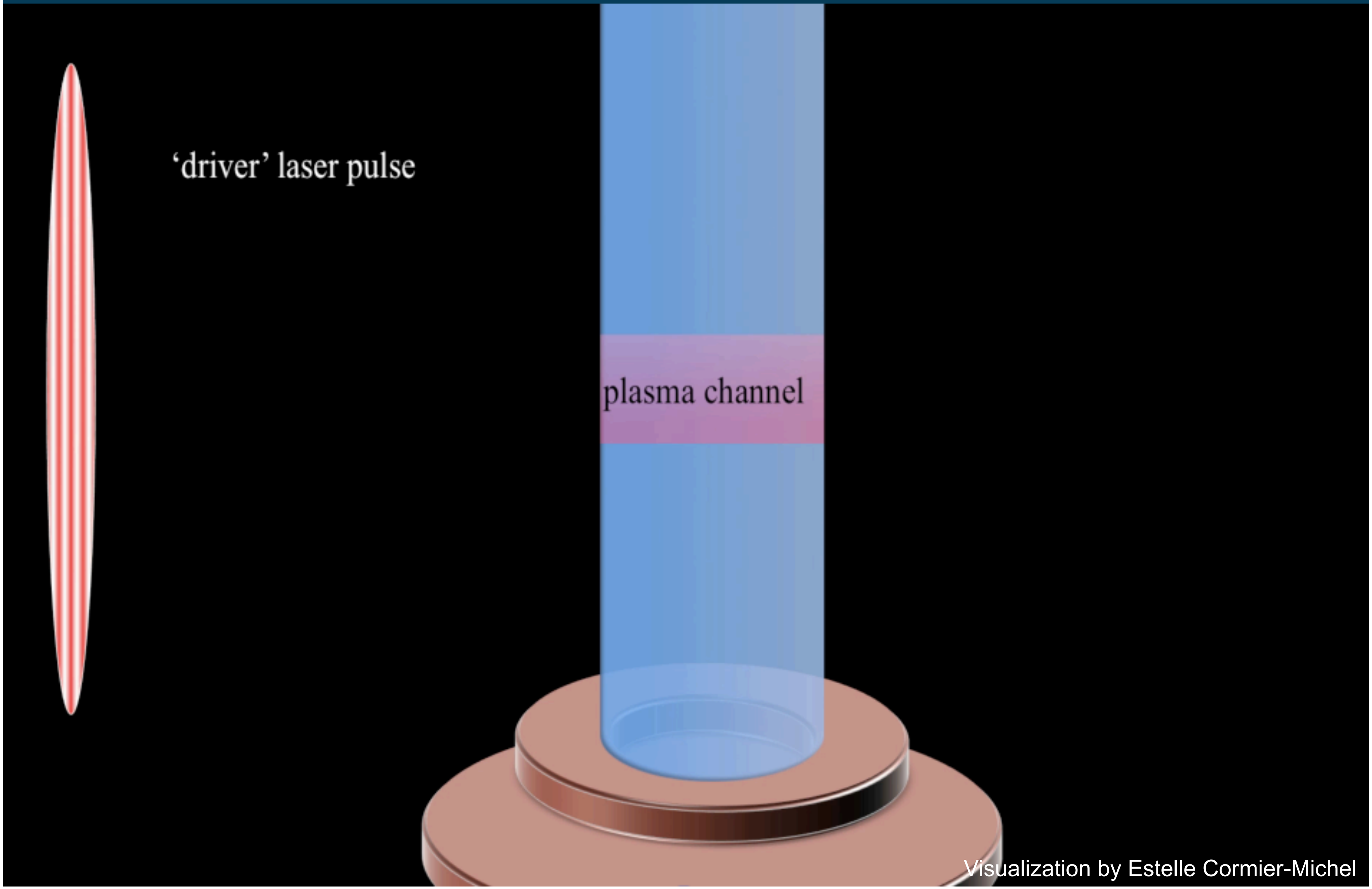
Laser Plasma Accelerators :
≥ 10 GeV/m gradient to reduce size of future linacs



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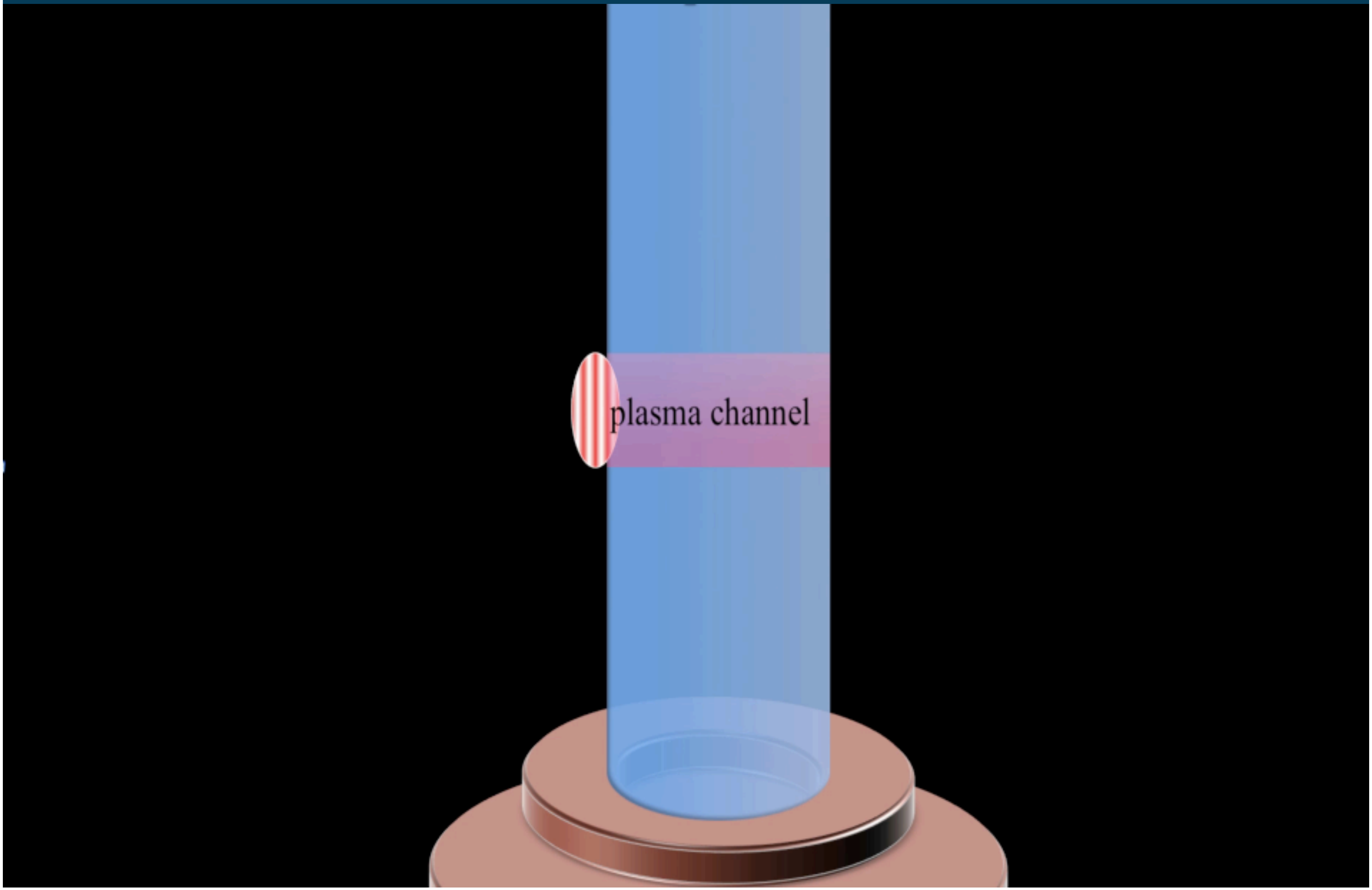

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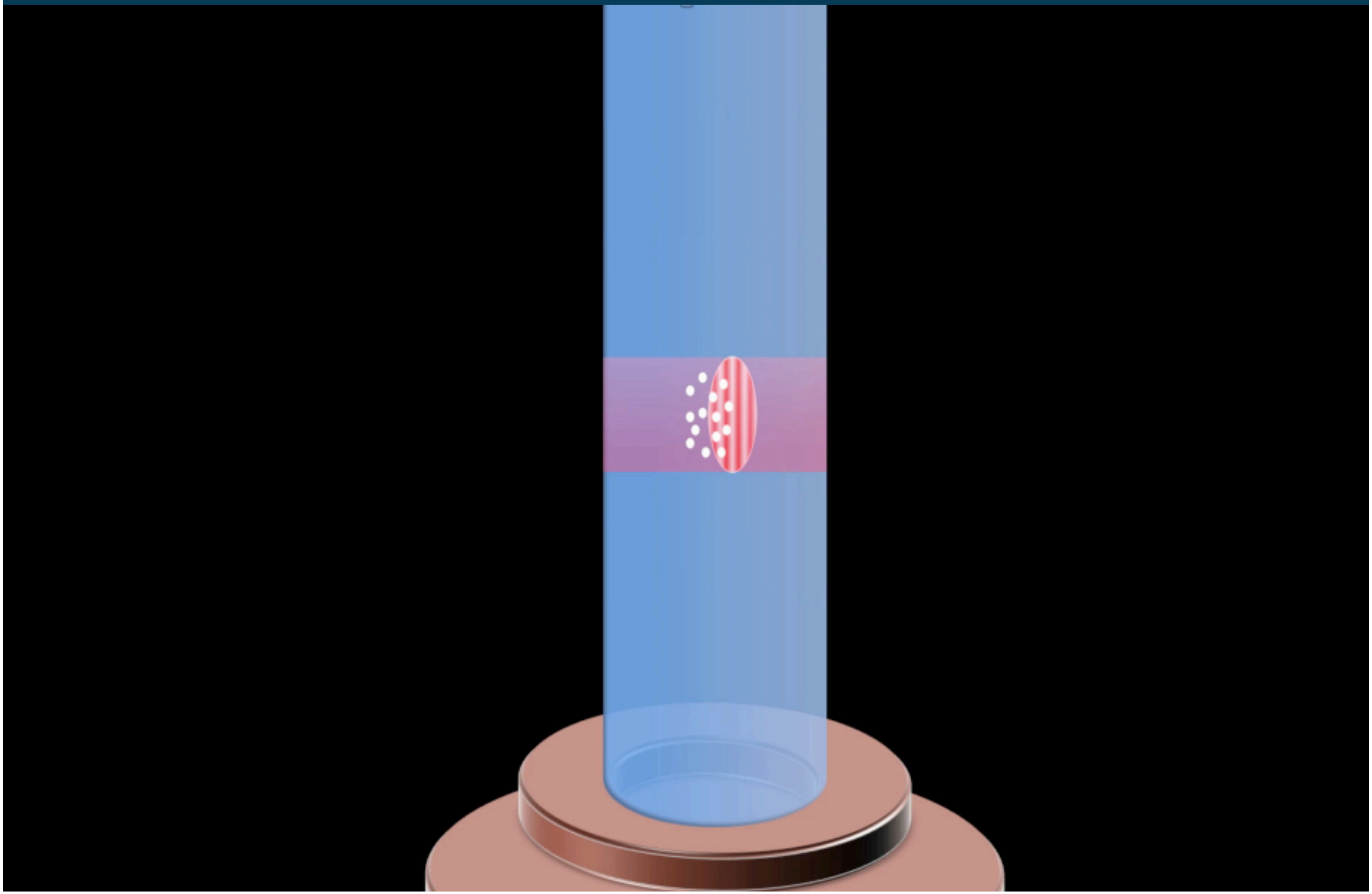
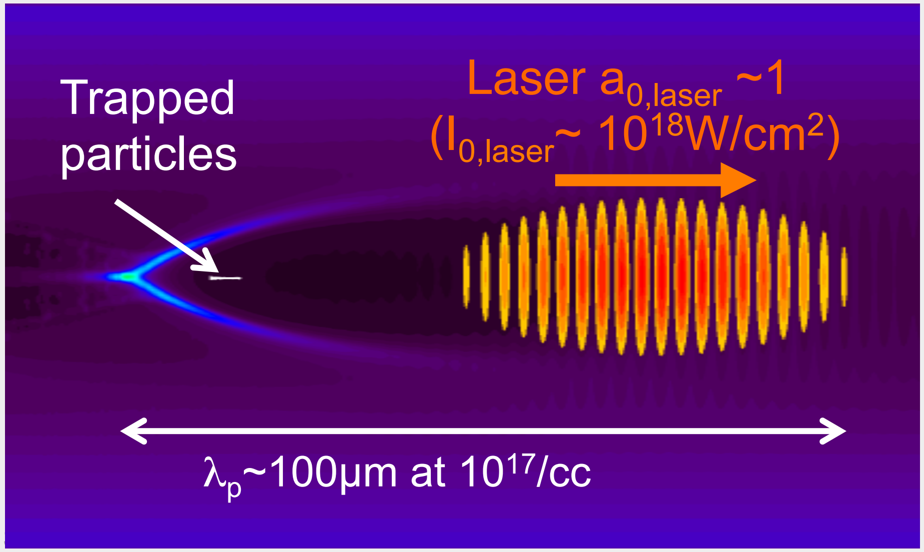


Laser Plasma Accelerators*: ≥ 10 GeV/m gradient to reduce size of future linacs

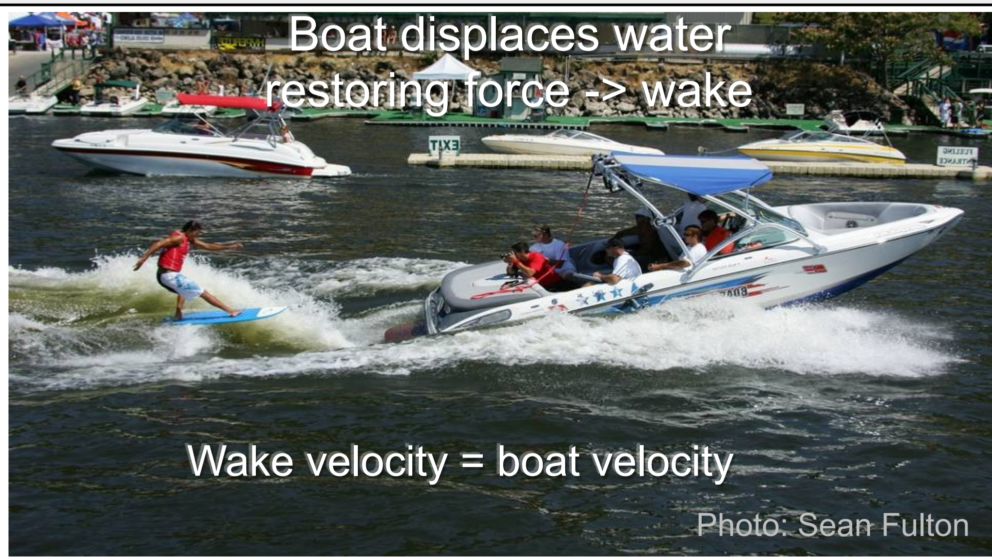


Space charge restoring force -> wakefield

$T_{laser} < T_{plasma}$ ~ 50fs

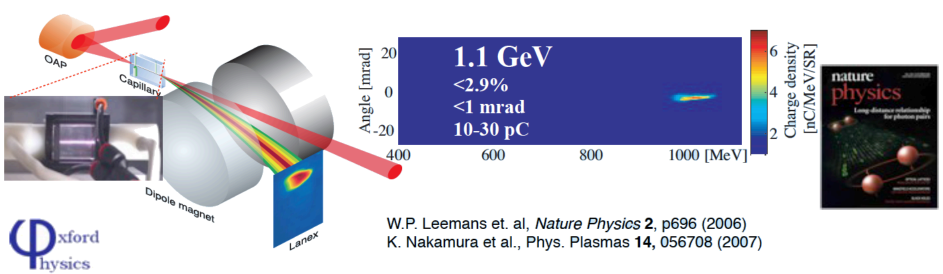
Accelerating fields ~ GeV per cm

Wake velocity ~ laser velocity



*T. Tajima and J.M. Dawson, PRL 1979
Esarey et al, Rev. Mod. Physics 2009

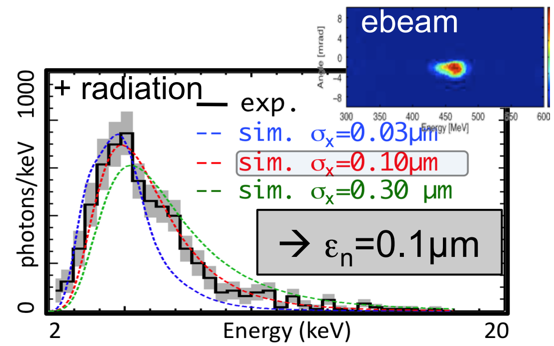
Laser Plasma Accelerators produce GeV beams with low emittance and ΔE



GeV beams in 3 cm capillary

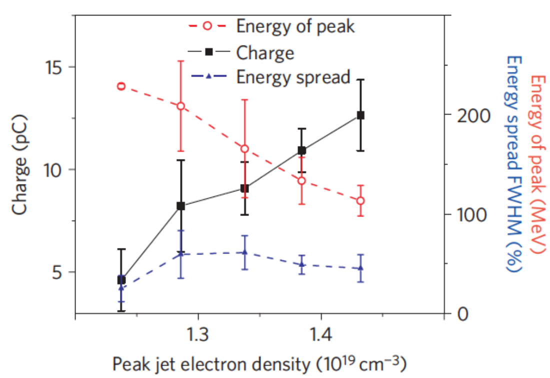
→PW lasers such as BELLA[1] producing 2 GeV, targeting 10 GeV

Leemans et al, Nature Physics 2006



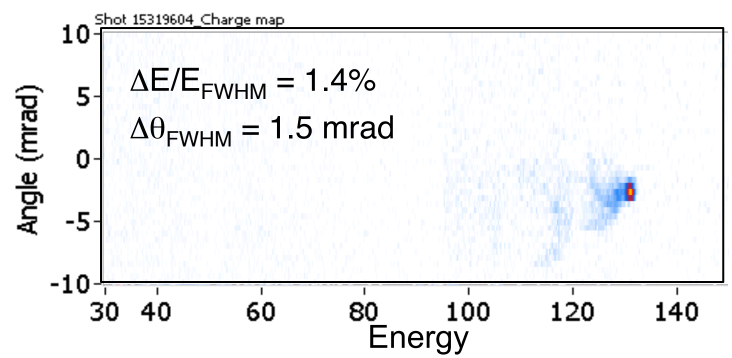
0.1 mm-mrad normalized emittance

Plateau et al, PRL 108, 2012
Related: Weingartner PRL 2012



Controlled injection & performance

Gonsalves et al., Nature Physics 2011
Related: Faure Nature Physics 2006



1% level integrated energy spread
sub – 1% slice energy spread

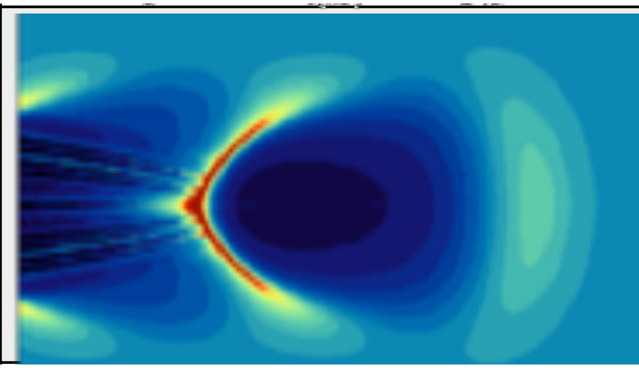
Related: Lin et al, PRL 108, 2012

Experiments on staging of multiple modules to increase energy are in progress[2]

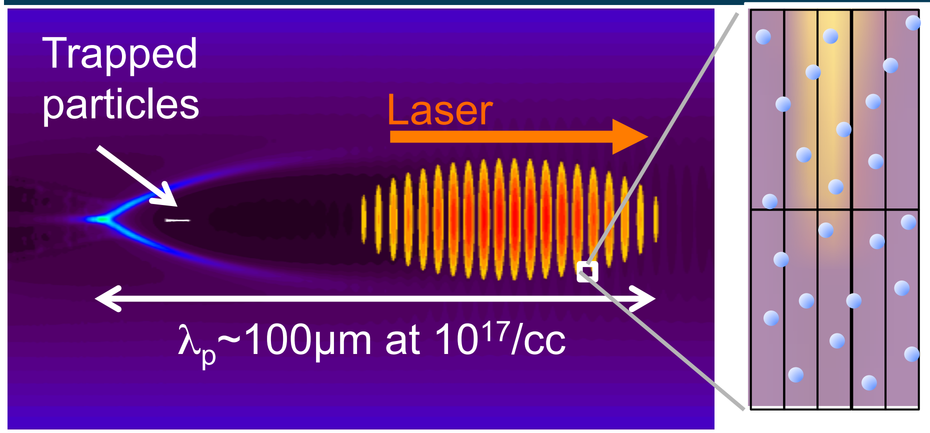
1: Leemans et al., Proc. Adv Accel. Wkshp 2010.

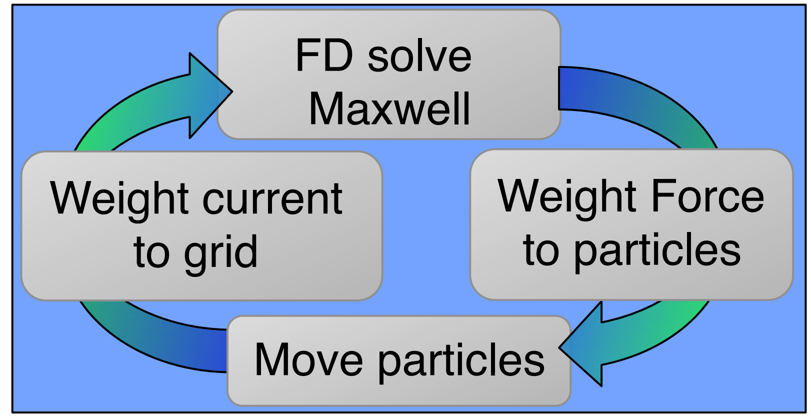
2: Shiraishi et al., Proc. Adv Accel. Wkshp 2012

LPA Simulation: EM plasma, with gas dynamics, radiation/scattering

Time scale	Physics	Codes	Example
ps/fs	• Laser-plasma interaction, focusing, ionization, depletion. • Injection/evolution of particle beams	EM Fluid, Particle-In-Cell VORPAL, INF&RNO, ALaDyn, WARP, REMP Related: OSIRIS, QuickPIC, VLPL…	

Core simulation:
EM plasma scales well, models cm-scale GeV LPAs





Explicit PIC/fluid simulates core LPA physics

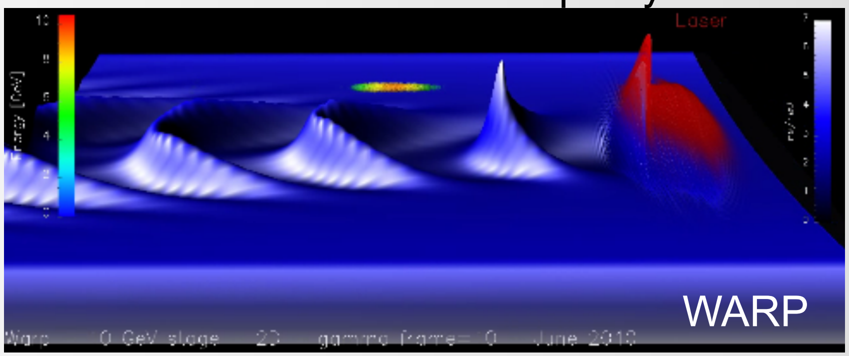
- Scale to >100kcore via domain decomposition
- Limits include area/volume and I/O scaling

For future high energy and high quality beams:

- Laser-to-plasma scale separation limits m-scale and beyond
- Accuracy issues: noise, numerical temperature, staggered grid

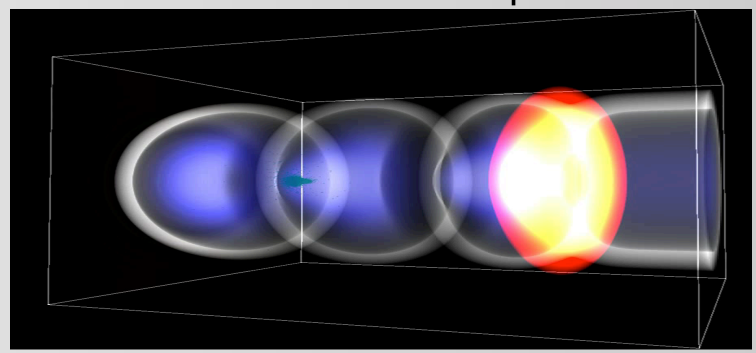
Plasma-physics based reduced models allow 10 GeV meter-scale simulations

Boosted computational frame^
reduces scale disparity



^VayPoP letter 11, JCP11, PoP submitted,.
related: Cormier (Tech X), Martins (UCLA/IST)

Laser envelope model§
reduced resolution requirement



§Benedetti PAC2011-INF&RNO r-z code at LBNL
related -Cowan JCP 2011 3D cartesian (TechX)

Supported design of BELLA PW laser and collider concepts[1]

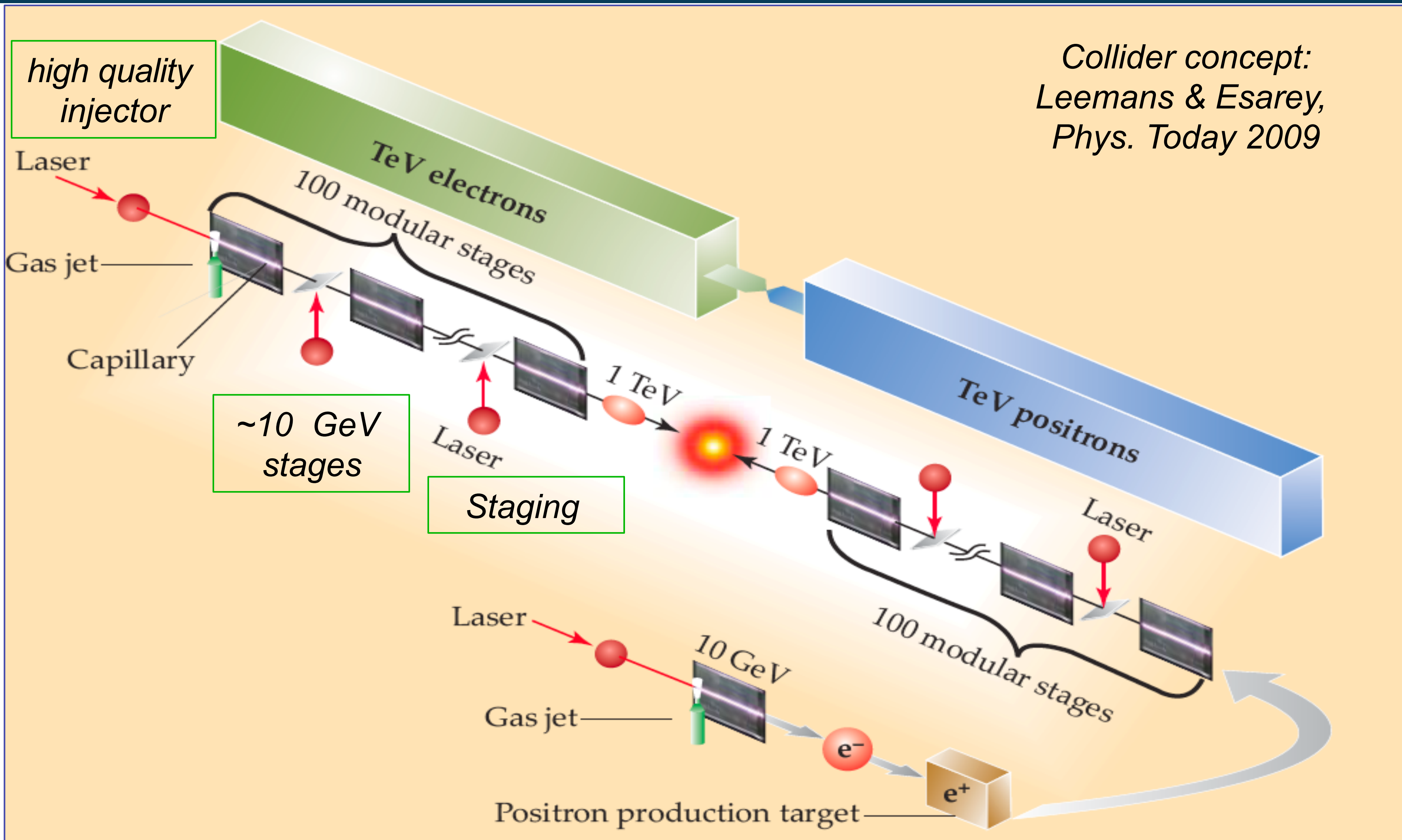
- Full scale required for correct emittance, focusing

Coupled with methods to reduce unphysical kinetic effects

- High order particles, smoothing, controlled dispersion and push

1: Leemans et al., Proc. Adv Accel. Wkshp 2010
Leemans & Esarey Physics Today 2009

Research focus: Physics/R&D challenges towards detailed conceptual design of a future collider



- Intermediate applications include FEL and Thomson gamma light sources
- Research needs detailed in Facilities group paper by J.P. Delahaye et al.

Physics capabilities for high-energy physics LPAs

Staging: order 100 LPAs, each of meter scale

Resolution of 10 nm – scale emittance

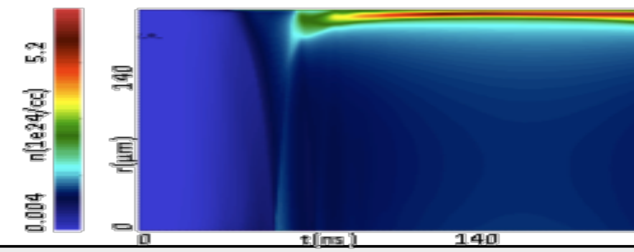
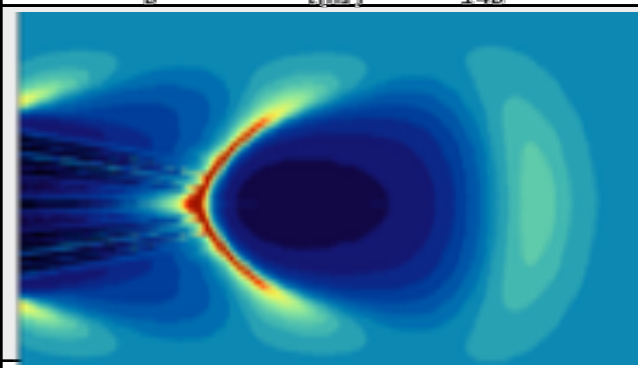
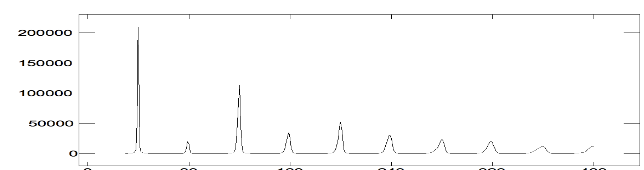
- Compact beam cooling methods
- Including scattering and radiation effects

Spin polarization and preservation

Positron production and acceleration/focusing

Compact final focus methods (e.g. adiabatic plasma lens)

LPA Simulation: EM plasma, with gas dynamics, radiation/scattering

Time scale	Physics	Codes	Example
ms	Gas target formation: capillaries and gas jets	Gas dynamics- ANSYS, OpenFOAM	
ns	Plasma formation in capillary discharges	MHD - Bobrova	
ps/fs	• Laser-plasma interaction, focusing, ionization, depletion. • Injection/evolution of particle beams	EM Fluid, Particle-In-Cell VORPAL, INF&RNO, ALaDyn, WARP, REMP Related: OSIRIS, QuickPIC, VLPL…	
	FEL, radiation, beam transport	GINGER, VDSR, GPT	

Radiation and Scattering models

Radiation from oscillations in strong focusing fields

- Used for betatron, Thomson scattering

Scattering from plasma particles, foils

Presently external to LPA simulations

- For collider distances / emittances integration to LPA sim. required

Computing capabilities for high-energy physics LPAs

Length of simulation and emittance accuracy increase 1-2 orders

- Domain size similar → weak scaling limited

Integrate models for e+ production, radiation, polarization

- Resolve quantization of radiation
- Correct statistics require increased particle number

Computing methods/requirements detail:
http://www.nersc.gov/science/hpc-requirements-reviews/HEP/case-studies/

Accelerator modeling science capabilities for high-energy physics LPAs

Scaling for particle number and resolution. Require:

- Common I/O libraries that achieve full bandwidth
- Parallel analysis with advanced mathematics, in-sit

Multicore/SIMD work well with PIC

- Need common tools, test beds, advance notice, het. decomp.

Compute power increasing faster than bandwidth

- High accuracy/long timestep methods, even at higher cost

New models for improved accuracy/ momentum fidelity

- Spectral, nodal, integrate accel. codes...
- Vlasov

Common to many codes

Specific dev.

Supporting capabilities for high-energy physics LPAs

Target formation

- 3D plasma formation including flow
- Heat deposition from laser
- Heat flow and extraction at kHz- MHz

Beam transport of fs, multi-kA beams

High average power lasers

- Materials, optical propagation/amplification, heat flow

Compute needs driven by requirement for Accuracy, low emittance, and 100-stage sim.

Estimates based on physics needs

	Present	**5 years**	**10 years**
Computation (Mhours)	15	500	10,000
Typical cores* for production runs	5000	50,000	50,000
Maximum cores* for production	16000	250-500k	5M
Data read and written per run (TB)	3 TB	100 TB	1000 TB
Minimum I/O bandwidth	0.3 GB/sec	10 GB/sec	100 GB/sec
Shared file-system space	20 TB	600 TB	6 PB
Memory requirement per core.	0.1 GB	0.1 GB	0.2 GB

Summary

EM PIC/fluid supported exp. at GeV in few cm, ΔE~1%, ε_n ~0.1 um

Address challenges for detailed conceptual design of a future collider

- 100's of 10 GeV stages, 0.01 um level ε_n → length, accuracy
- Integrate: e^+, radiation, scattering, polarization…
- Add: Cooling, focusing, 3d target formation, heat flow, laser

Requires combination of:

- Scaling (incl. I/O & analytics), new physics models/solvers, new computing architectures

White paper on
DOE-HEP Accelerator Modeling Science Activities

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Goal (from the draft charge):

"maximizing the impact of computer modeling on the design of future particle accelerators and the development of new accelerator techniques & technologies."

This white paper presents the rationale for:

a. strengthening and expanding programmatic activities in accelerator modeling science within DOE-HEP,

b. increasing the community-wide coordination and integration of code development.

Importance of modeling is on the rise

with increasing:

- pressure for **reducing uncertainties** and **cost** on development, construction & commissioning of accelerator,
- accuracy of codes with **better algorithms** and **more physics,**
- **computers capacity.**

`

Resources optimization calls for balanced approach

Maximizing the overall scientific output/$ means:

- **maximizing usability** of the pool of codes:
  - **effectiveness** (completeness, accuracy of solution),
  - **efficiency** (time to solution),
  - **ease of use** (learnability, error tolerance, versatility, etc.),
- while **minimizing spending** on development and support:
  - **reduction of duplication**,
  - increase in **modularity** and **code interoperability**.

Implies comprehensive strategy that evaluates codes

- not only based on **performance**, **effectiveness**, **ease of use**, levels of **documentation** and **support**,
- but also on other attributes such as **modularity**, **flexibility**, **reusability**, **expandability** and **interoperability**.

March toward exascale brings extra challenges

Next generation of High Performance Computers

- will provide **high-accuracy integrated simulations**, **better design optimization**, **near real-time modeling**, …

- eventually leading to ***virtual accelerators*** (including virtual "control room").

But with increased heterogeneity and level of parallelism:

➔ programming of next generation computers will require **new** or **reworked codes** with **new exascale-ready algorithms**.

Beam & Accelerator Modeling Science

is increasingly relevant as a **programmatic activity:**

- timely to go **beyond code development** and application in support of theory and experiments,
- development and application of accelerator algorithms/codes are **very complex** and **specialized tasks,**
- need for **dedicated teams** <u>within</u> **HEP** (in collab. w/ ASCR):
    - **physicists** + **applied math** + **computer scientists**
    - to develop codes **w/ more physics** on **more complex** machines
    - examples elsewhere of such dedicated teams:
        - MPI Garching, Germany - MFE-ITER
        - Saclay, France – CILEX-LPA/laser applications

Need for coordination into a cohesive tool set

Numerous beam/accelerator codes **developed worldwide :**

- offer **wide array of options** to modelers,
- but **cohesion is lacking**, w/ some **duplication** & **inefficiency**.

Usual paradigm (with very few exceptions)**:**

- **one** developer (physicist)/**topic/project**
  - **occasional** help from **computer scientist/applied math**.
- leads to **many small specialized** codes
  - **lack breadth** required for **integrated multi-physics** modeling

Integrated multi-physics modeling calls for **more cohesion**

Portfolio should cover from low- to high-end computing

Supercomputers aggregate of **many "off-the-shelf" units:**

- each unit **similar** or **same** as on **desktops** or **laptops**
- development now **often** on **laptops/desktops/small clusters**:
  - **faster turnaround** for development, testing, debugging

Desktops/laptops are becoming more **powerful**

- will soon integrate tens of cores
- can **tackle** many **low-** to **medium-** range modeling

Separation between **low-** & **high-end** computing is **vanishing**

Need **comprehensive** program covering **low-** **to** **high-end**

Need and solution for non-disruptive integration

Significant investments of **HEP** into **existing** pool of codes:

- essential to **minimize disruptions** to **developers** and **users,**
- while **enabling interoperability** and **expandability**.

Python scripting language has **unique attributes:**

- **rapid development** and **prototyping of scientific applications**
  - **on par** with e.g. **Maple, Matlab** (which it is often supplanting)
- is **expandable** and couples to **FORTRAN**, **C** and **C++**

Ideal for **coupling existing codes** with **minimized disruptions**

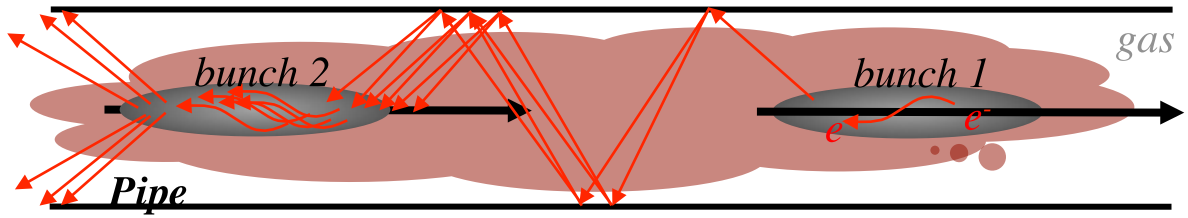
- codes **continue unmodified** but **functionalities** are **exposed**

➔ integrated tool set of **unprecedented power** and **versatility**.

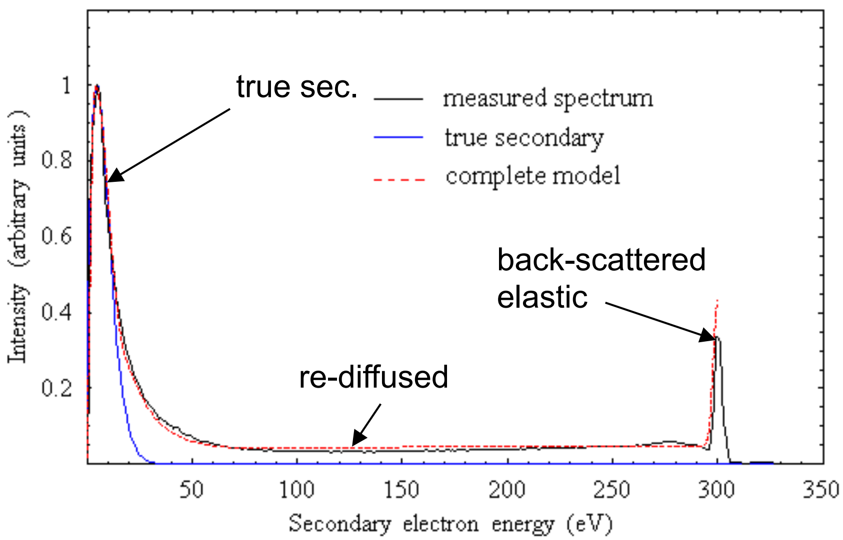
Example #1: Warp and Posinst integrated in a modular "combo" package

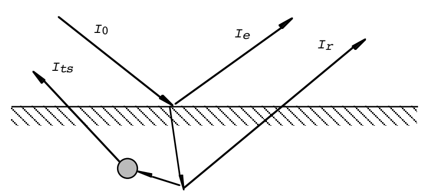
Enabling fully self-consistent modeling of e⁻ cloud effects: *build-up* & *beam dynamics*:

- Beyond standard practice of simulating e- cloud buildup (ECLOUD, Vorpal, etc) and then its effect on beams (Headtail, SYNERGIA, etc)



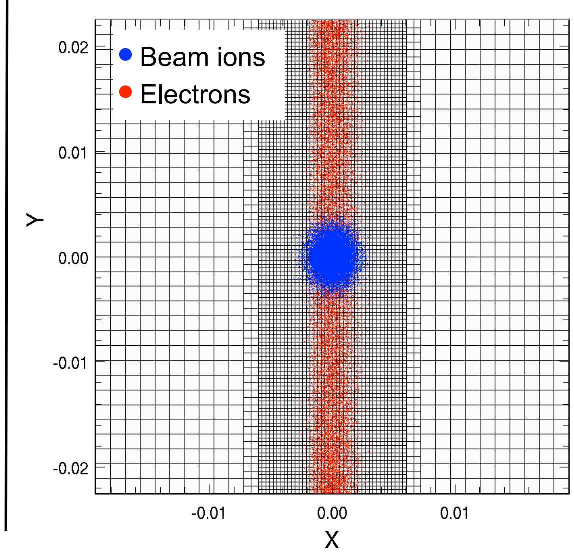
Posinst provides advanced secondary electrons model (and optional particle pusher).





Monte-Carlo generation of electrons with energy and angular dependence.

Warp's mesh refinement & parallelism provide efficiency.

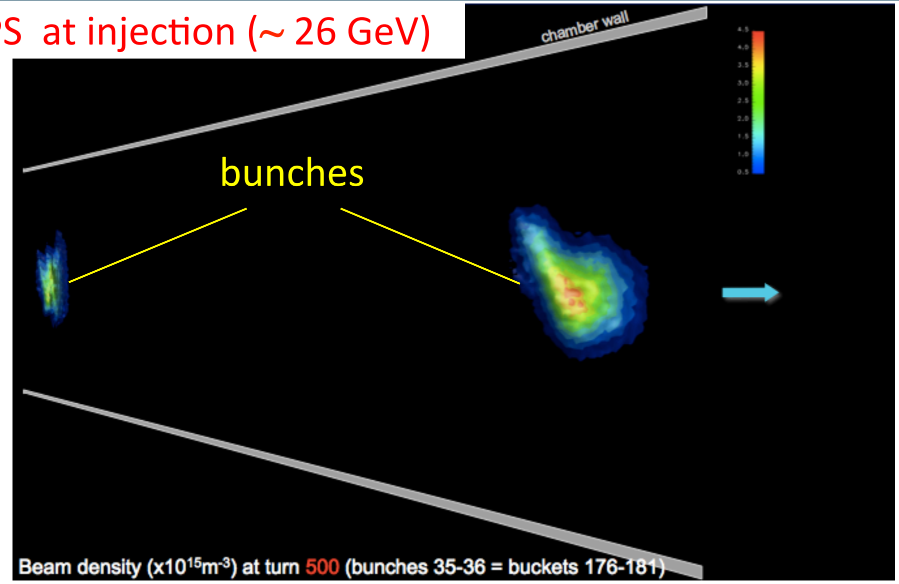


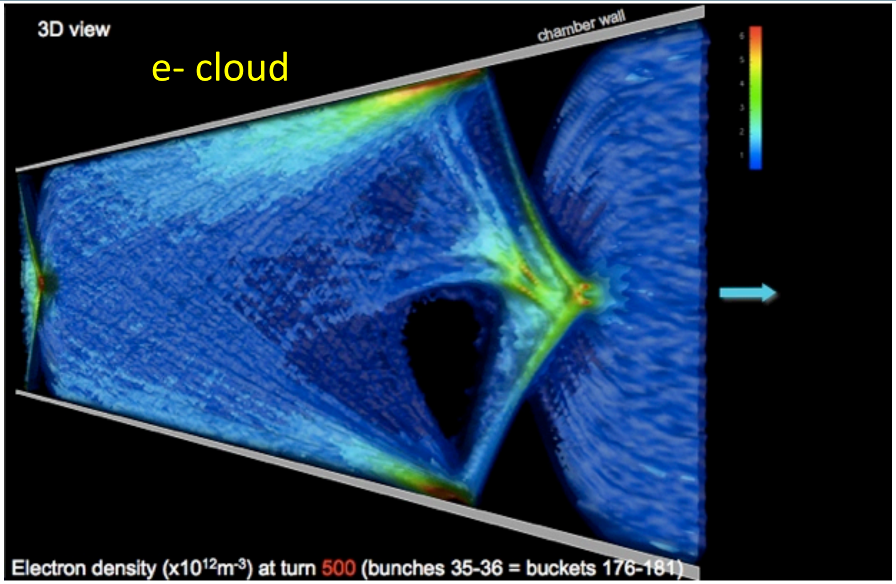
Python programming language is the glue between Warp and Posinst

First direct simulation of a train of 3x72 bunches
-- using 9,600 CPUs on NERSC supercomputer

SPS at injection (~ 26 GeV)

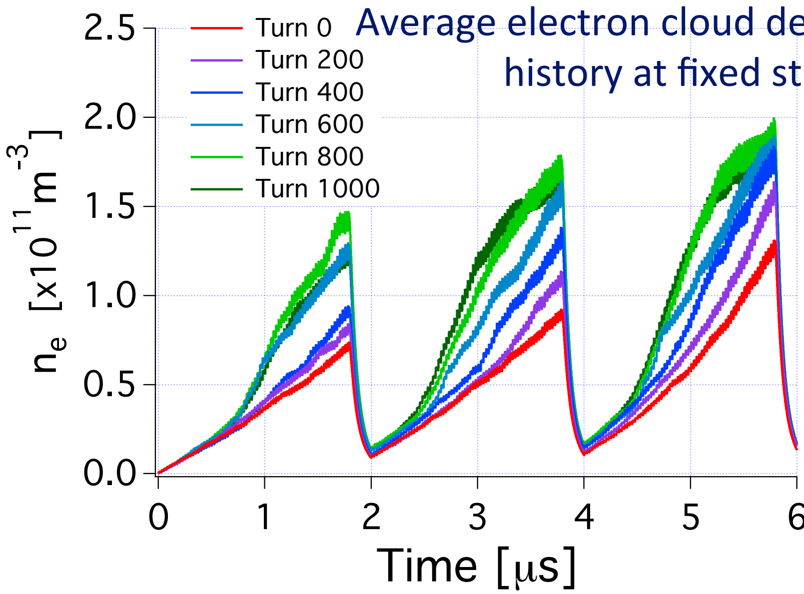
Turn 500





- Unexpected e^- density rise in tails of batches between turns 0 and 800*.

Average electron cloud density history at fixed station



*J.-L. Vay, et al, *IPAC12 Proc.*, (2012) TUEPPB006

Example #2: Warp & Icool combined with Python and applied to muon cooling in US MAP

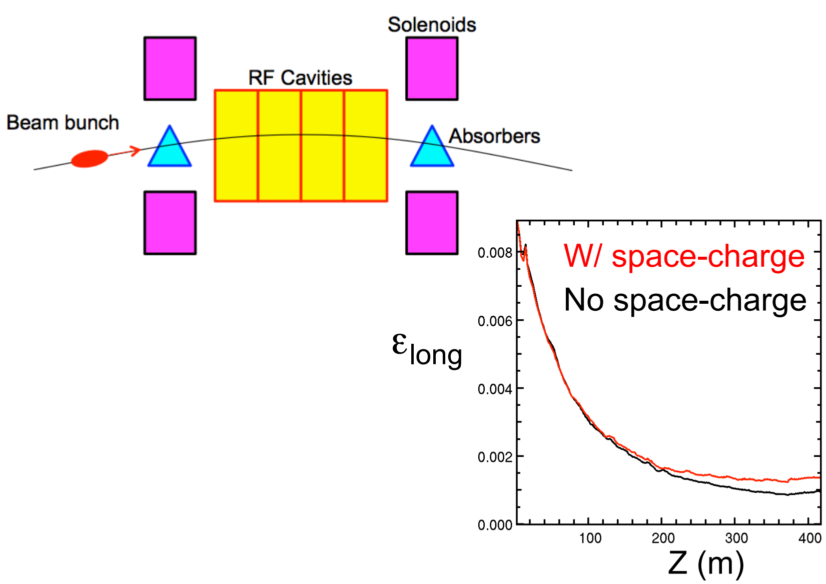
Warp: particle tracking plus self fields

ICOOL: absorption

No changes to ICOOL (except skipping main routine)

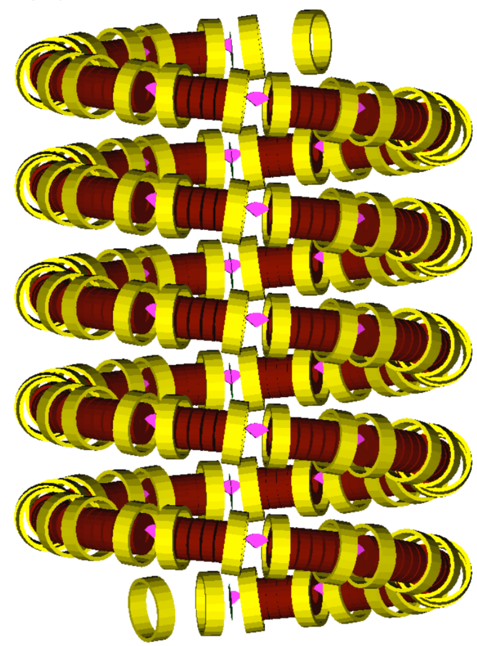
Particle handling in Python – passing appropriate particles to ICOOL

Initial 2-D RZ simulation results show reduced cooling when including space-charge



Full characterization requires 3-D (in progress):

- Current cooling lattice is a tapered helical line
- Simulation needs to include curvature and transverse dispersion



Summary

(a) Expanding accelerator modeling science activities

- **importance of modeling is on the rise**
  - better codes, computers, pressure to control cost
- **resources optimization calls for balanced approach**
  - emphasize also modularity, interoperability, …
- **march toward exascale brings extra challenges**
  - requires new codes with new exascale-ready algorithms

➔ **needs programmatic beam/accelerator modeling science**
  - with integrated teams (phys. + math. + comput.)

Summary

(b) Increasing community-wide coordination & integration

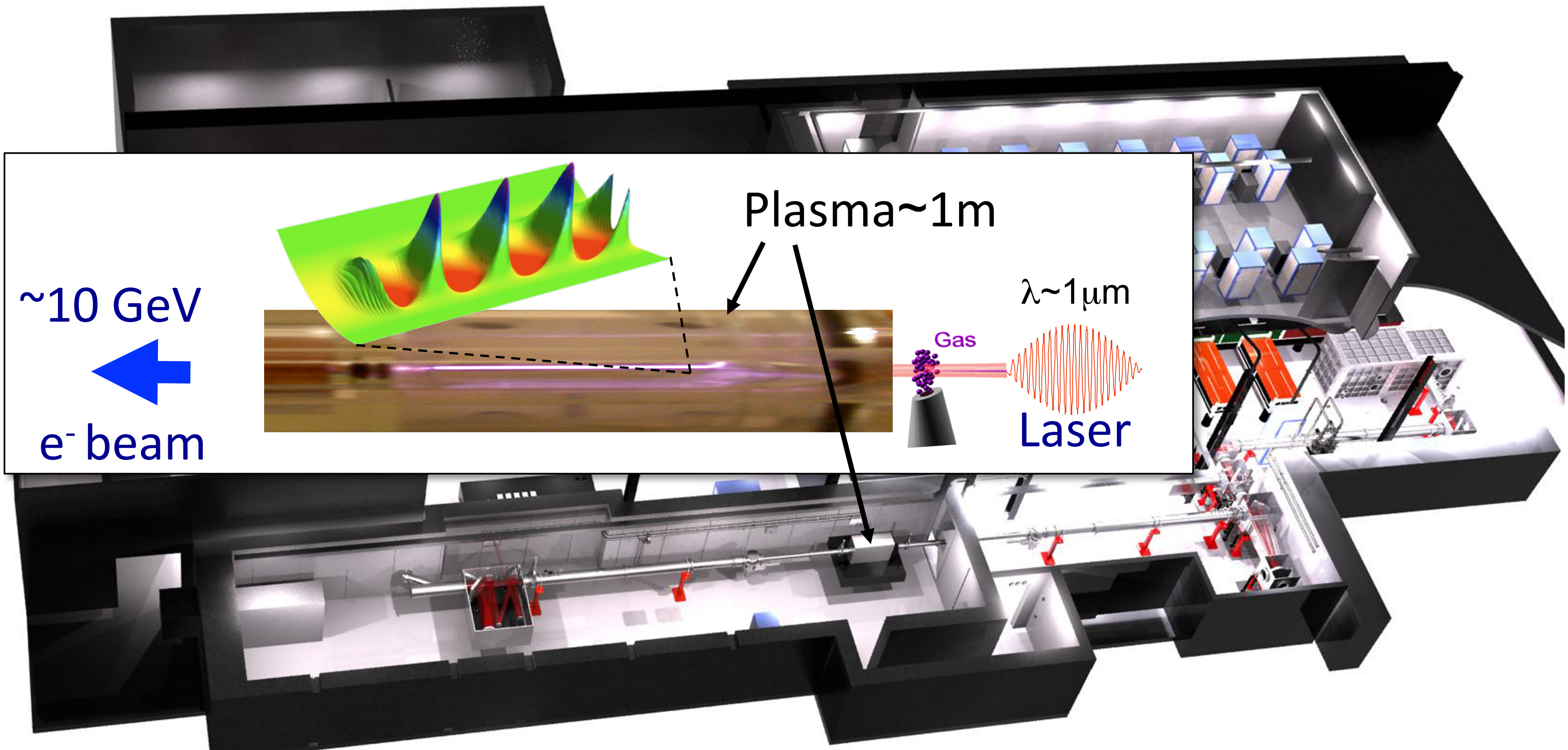
- **need for coordination into a cohesive tool set**
  - integrated multiphysics modeling calls for more cohesion
- **portfolio should cover from low- to high-end computing**
  - separation between low- & high-end computing is vanishing
- **need for non-disruptive integration**
  - many existing codes used by many users for study & design
- **Python stands out as solution for progressive coupling**
  - codes continue unmodified but functionalities are exposed

➔ integrated tool set of **unprecedented power** and **versatility**.

Backup material

BELLA laser in operation at LBNL :
10 GeV Collider relevant module

- State of the art 1 PW, 1Hz, 40 fs
  - Commercial system with Strehl > 0.9
- Simulations show 10 GeV in 0.1-0.5 m – experiments in progress



Leemans, Proc. Adv. Accel. Concepts Workshop 2010